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Dynamic building performance assessment using calibrated simulation

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ABSTRACT

Accurate building performance assessment is necessary for the design of efficient energy retrofit operations and to foster the development of energy performance contracts. An important barrier however is that simulation tools fail to accurately predict the actual energy consumption. We present a methodology combining thermal sensor output and inverse algorithms to determine the key parameters of a multizone thermal model. The method yields calibrated thermal models that are among the most detailed ones in the literature dealing with building thermal identification. We evaluate the accuracy of the resulting thermal model through the computation of the energy consumption and the reconstruction of the main energy flux. Our method enables one to reduce standard uncertainties in the thermal state and in the quantities of interest by more than 1 order of magnitude.

1. Introduction

Energy retrofitting of the buildings stock is a major challenge to substantially reduce energy consumption in European countries. Energy performance contracts are a powerful tool to foster ambitious retrofit operations but their development is slowed down by the lack of accurate performance analysis tools. As a matter of fact, simulation tools used to assess the energy performance of existing buildings and design energy conservation measures lead to discrepancies between actual and computed energy performance, and thus fail to predict accurately the energy consumption after retrofit [32,27,5,12]. Techniques to obtain calibrated simulation models are still needed and this has been an active research area in the two last decades [1,2,29,28,16,37,26].

The literature on the topic often takes the direction of model simplification: in this approach, one looks for a sufficient prediction model that involves a few number of parameters that can be identified using a given set of measurement data. These methods are able to predict the overall thermal state, but lack insight into building parameters. They are particularly suitable for control problems. Many works on model reduction highlight the importance of the suitable choice of the model parameters [15,18,23].

The opposite direction consists in trying to correct the response of a detailed simulation model by adjusting some key parameters in the model. This leads to a problem that is usually more difficult to tackle because of the large number of parameters involved in a detailed simulation model compared to the available measured data.

Considering that a detailed simulation model is essential for the design of efficient energy retrofit measures, we address here the question of calibrating a simulation model based on standard dynamic multizone assumptions. The choice of such a detailed model enables to characterize all energy fluxes in the building under study, evaluate the true potential of refurbishment scenarios, and offers to the engineer in depth analysis of the building's behavior.

Model calibration can be treated in the context of inverse problems theory. The development of inverse problem approaches to building simulation goes back to the 1980s [30]. Using this framework, we solve here a state-parameter identification problem which aims at determining sources and intrinsic properties of a mathematical model based on partial observations of the physical state [3]. This kind of non-linear problems may be reformulated as optimization problems, where the unknowns are sought as minimizers of a cost-function evaluating the gap between the computed and the measured physical state [34].

Special attention is given to assess the quality of the model that is obtained regarding two main criteria. The first is related to the ability of the model to accurately compute the energy needs in a

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Table 1
Flux definition in the zones, with θ_s the wall temperature and Θ_z the heating device temperature.

Flux	Definition
$\mathcal{A}_{rz} = c_a R_{zr}(T_r - T_z)$	Interzone airmass exchange
$\bar{\mathcal{A}}_z = c_a q_z (T_a - T_z)$	Airmass exchange with outside environment
$\mathcal{C}^0_{sz} = h^0_{sz}(\theta_s(0,t) - T_z)$ $\mathcal{C}^L_{sz} = h^L_{sz}(\theta_s(L_s,t) - T_z)$	Convection between surfaces and inside air
$\mathcal{Q}_z = \sum_i Q^i_z$	Internal gains from people and equipment
$\mathcal{W}_z = \lambda_z(\Theta_z - T_z)$	Convective gains from heating devices
$\Phi^b_z = A_z \tau_z \gamma^b_z \phi^b$ $\Phi^d_z = A_z \tau_z \gamma^d_z \phi^d$	Gains from short-wave solar radiation through windows

building. The second one is related to its ability to compute the main energy fluxes that compose the thermal dynamical equilibrium of the building. We call quantities of interest the variables associated to these two criteria; they represent crucial information for the evaluation of refurbishment scenarios impact and return on investment. They are also a fundamental tool in the development of energy performance contracts.

The paper is organized as follows. First, we present the main modeling assumptions that are used and introduce a simple geometry that will be used for a case study. In the next section, we present the approach used for the resolution of the identification problem, based upon optimal control theory. The last section concerns various numerical tests that help evaluate the performance of the calibrated model under various situations with respect to the two above-mentioned criteria.

2. Modeling assumptions and case study

In this section, we first introduce the mathematical model used for this work. As explained before, it is a detailed building thermal model. We then present the case study and give mathematical definitions for the quantities of interest.

2.1. Thermal model for building energy diagnosis

The thermal model used in this work follows the standard multizone modeling assumptions: we consider homogeneous spatial distribution of the temperature field in the zones, and one-directional heat flux through walls [4]. Multizone models directly derived from a continuous 3D formulation where fluids and solids are coupled by boundary layer exchange with Robin transmission conditions on interfaces [6,8].

The room air temperature is governed by an ordinary differential equation (ODE) evaluating the heat balance at the thermal node. Let $z \in [\![1, N_z]\!]$ be the zone index, with N_z the number of zones, and T_z the corresponding air temperature. The heat balance equation writes:

$$\begin{cases} C_z \dfrac{dT_z}{dt} = \displaystyle\sum_{r=1}^{N_z} \mathcal{A}_{rz} + \bar{\mathcal{A}}_z + \sum_{s=1}^{N_s} S_s(\mathcal{C}^0_{sz} + \mathcal{C}^L_{sz}) + \mathcal{Q}_z + \mathcal{W}_z + \Phi^b_z + \Phi^d_z \\ T_z(t=0) = T^0_z \end{cases} \tag{1}$$

All terms are described in Table 1, they account for solar gains, convective gains through walls (no matter the aeraulics) and air exchange, and internal gains from people and equipment. What we called convective gains actually account for both convection and conduction exchanges in boundary layers between zones and surfaces. We note c_a the air heat capacity (J/K m^3), R_{zr} the airflow rate between zones z and r (m^3/s), q_z the air renewal rate (m^3/s), T_a the mean outside air temperature (K), h^0_{sz} (resp. h^L_{sz}) the convective heat exchange coefficient between surface s at surface ($x = 0$) (resp. ($x = L_s$)) and zone z (J/K m^2 s), $\theta_s(x, t)$ the surface temperature (K), Q^i_z the internal gains from use (J/s), λ_z the convective coupling between the heating device and the zone (J/K s), Θ_z the surface temperature of the heating device (K), A_z the windows area (m^2), γ^b_z (resp. γ^d_z) the beam (resp. diffuse) sun exposure coefficients for zone z, and ϕ^b (resp. ϕ^d) the beam (resp. diffuse) component of the solar flux (J/m^2 s).

Table 2
Flux definition on the walls' boundaries.

Flux	Definition
$\mathcal{R}^{00}_{sp} = \alpha^{00}_{sp}(\theta_p(0,t) - \theta_s(0,t))$ $\mathcal{R}^{0L}_{sp} = \alpha^{0L}_{sp}(\theta_p(L_p,t) - \theta_s(0,t))$ $\mathcal{R}^{L0}_{sp} = \alpha^{L0}_{sp}(\theta_p(0,t) - \theta_s(L_s,t))$ $\mathcal{R}^{LL}_{sp} = \alpha^{LL}_{sp}(\theta_p(L_p,t) - \theta_s(L_s,t))$	Longwave radiation exchange between adjacent surfaces facing each other
$\mathcal{R}^{0\infty}_s = \beta^0_s(T^\infty - \theta_s(0,t))$ $\mathcal{R}^{L\infty}_s = \beta^L_s(T^\infty - \theta_s(L_s,t))$	Longwave radiation between surfaces and the sky
$\bar{\mathcal{C}}^0_s = \bar{h}^0_s(T_a - \theta_s(0,t))$ $\bar{\mathcal{C}}^L_s = \bar{h}^L_s(T_a - \theta_s(L_s,t))$	Convection exchange between surfaces and outside environment
$\underline{\mathcal{C}}^0_s = \underline{h}^0_s(T_g - \theta_s(0,t))$ $\underline{\mathcal{C}}^L_s = \underline{h}^L_s(T_g - \theta_s(L_s,t))$	Conduction between surfaces and the ground
$\Phi^{b0}_s = \alpha^0_s \gamma^{0b}_s \phi^b$ $\Phi^{d0}_s = \alpha^0_s \gamma^{0d}_s \phi^d$ $\Phi^{bL}_s = \alpha^L_s \gamma^{Lb}_s \phi^b$ $\Phi^{dL}_s = \alpha^L_s \gamma^{Ld}_s \phi^d$	Shortwave solar radiation

Heat transfers within opaque walls and glazings are described by partial differential equations (PDE) with scalar equivalent thermal parameters [9,36]. Let $p \in [\![1, N_s]\!]$ be the surface index, with N_s the number of surfaces, and θ_s the corresponding temperature field. The temperature field θ_s is governed by the following equation:

$$\begin{cases} S_s \rho c_s \dfrac{\partial \theta_s}{\partial t} - S_s \dfrac{\partial}{\partial x}\left(k_s \dfrac{\partial \theta_s}{\partial x}\right) = 0, \qquad (x,t) \in [0, L_s] \times (0, t_a] \\ -k_s \dfrac{\partial \theta_s}{\partial x}(0,t) = \displaystyle\sum_{p=1}^{N_s} (\mathcal{R}^{00}_{sp} + \mathcal{R}^{0L}_{sp}) + \mathcal{R}^{0\infty}_s - \sum_{z=1}^{N_z} \mathcal{C}^0_{sz} + \bar{\mathcal{C}}^0_s + \underline{\mathcal{C}}^0_s + \Phi^{b0}_s + \Phi^{d0}_s \\ k_s \dfrac{\partial \theta_s}{\partial x}(L_s,t) = \displaystyle\sum_{p=1}^{N_s} (\mathcal{R}^{L0}_{sp} + \mathcal{R}^{LL}_{sp}) + \mathcal{R}^{L\infty}_s - \sum_{z=1}^{N_z} \mathcal{C}^L_{sz} + \bar{\mathcal{C}}^L_s + \underline{\mathcal{C}}^L_s + \Phi^{bL}_s + \Phi^{dL}_s \\ \theta_s(x, t=0) = \theta^0_s(x) \end{cases} \tag{2}$$

All terms are described into Table 2, they account for solar gains, convective gains through the environment, and radiative gains from adjacent facing surfaces and from the sky. We note α^{0L}_{sp} the radiative exchange coefficient between the face ($x = 0$) of surface s and the face ($x = L_p$) of surface p (J/K m^2 s), β^0_s (resp. β^L_s) the radiative exchange coefficient between the face ($x = 0$) (resp. ($x = L_s$)) of surface s and the sky (J/K m^2 s), T^∞ the equivalent sky temperature (K), $\bar{h}^0_s$ (resp. $\bar{h}^L_s$) the convective heat exchange coefficient between the face ($x = 0$) (resp. ($x = L_s$)) of surface s and the outside air (J/K m^2 s), T_a the mean outside air temperature (K), $\underline{h}^0_s$ (resp. $\underline{h}^L_s$) the diffusive heat coefficient between the face ($x = 0$) (resp. ($x = L_s$)) of surface s and the ground (J/K m^2 s), T_g the ground temperature (K), α^0_s (resp. α^L_s) the absorbance of the face ($x = 0$) (resp. ($x = L_s$)) of surface s, γ^{0b}_s (resp. γ^{0d}_s) the exposure coefficient to the beam (resp. diffuse) solar component of the face ($x = 0$) of surface s, and ϕ^b (resp. ϕ^d) the beam (resp. diffuse) component of the solar flux (J/m^2 s).

We also consider a model for the thermal behavior of heat devices inside the zones. Let Θ_z be the temperature of the heating device $z \in [\![1, N_z]\!]$, given as the solution of the following ODE:

$$\begin{cases} d_z \dfrac{d\Theta_z}{dt} = \mathcal{P}_z - \mathcal{W}_z \\ \Theta_z(t=0) = \Theta^0_z \end{cases} \tag{3}$$